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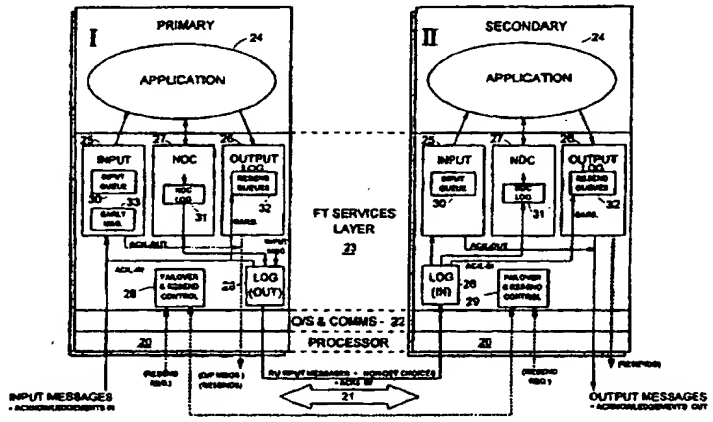

(57) Abstract

A recovery unit in a software fault-tolerant system has primary and secondary processing units (I, II) running replicate application processes (24). Input messages sent to the recovery unit are received at the primary unit (I) and in due course processed by the primary process (24) to produce application messages; however, these application messages produced by the primary process (24) are not normally output from the recovery unit. The input messages received at the primary unit (I) are logged to the secondary unit (II) together with any non-deterministic choices made by the primary process during its processing. The secondary process (24) processes the input messages logged to the secondary unit (II) in the same order as the primary process (24) with any non-deterministic choices made by the primary process in its processing being used by the secondary process in place of the latter making its own non-deterministic choices during processing. The application messages produced by the secondary process (24) are used as the output messages of the recovery unit. Should the primary unit (I) fail, the secondary unit (II) takes over the role of the primary. Furthermore, in the absence of an operative secondary unit (II) (due either to its failure or to its promotion to the primary unit), the recovery-unit output messages are provided from the processing effected by the primary process. Configurations with multiple secondaries are also possible.

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FAULT-TOLERANT PROCESSING METHOD

Field of the Invention

The present invention relates to a fault-tolerant processing method for receiving and processing input messages to produce output messages. More particularly, the present invention relates to a method of operating a software fault tolerant recovery unit where the processing of input messages is done by replicate primary and secondary application processes.

It should be noted that the term "process" is used herein in a general sense of processing functionality provided by code executing on a processor however this code is organised (that is, whether the code is an instance of only part of a program, or of a whole program, or is spread across multiple programs). Furthermore, reference to a process as being an "application" process is intended to be understood broadly in the sense of a process providing some desired functionality for which purpose input messages are sent to the process.

Background of the Invention

Software-based fault-tolerant systems may be considered as organised into one or more recovery units each of which constitutes a unit of failure and recovery. A recovery unit may be considered as made up of a live process, an arrangement for logging recovery information relevant to that live process, and recovery means, which in the event of failure of the live process, causes a replacement process to take over.

Of course, if failure of the live process due to failure of the processor running it is to be covered, then both the storage of recovery information and the recovery means itself must be separate from the processor running the live process.

Where a system comprises multiple recovery units, these will typically overlap in terms of processor utilisation; for example, the processor targeted to run the replacement process for a first recovery unit, may also be the processor running the live process of a second recovery unit. In fact, there may also be common resource utilisation by the recovery units in respect of their logging and recovery means.

An illustrative prior-art fault-tolerant computer system is shown in Figure 1 of the accompanying drawings. This system comprises three processors I, II, III and a disc unit 10

all interconnected by a LAN 11. The system is organised as two recovery units A and B each of which has an associated live process A/L , B/L . Live process A/L runs on processor I and live process B/L runs on processor II. Recovery unit A is arranged such that upon failure of its live process A/L, a replacement process A/R will be take over on processor II; similarly, recovery unit B is arranged such that should live process B/L fail, a replacement process B/R takes over on processor III.

A live process will progress through a succession of internal states depending on its deterministic behaviour and on non-deterministic events such as external inputs (including messages received from other live processes, where present) and non-deterministic internal events.

When a replacement process takes over from a failed live process, the replacement process must be placed in a state that the failed process achieved (though not necessarily its most current pre-failure state). To do this, it is necessary to know state information on the live process at at least one point prior to failure; furthermore, if information is also known on the non-deterministic events experienced by the failed process, it is possible to run the replacement process forward from the state known about for the failed process, to some later state achieved by the latter process.

Where speed of recovery is not critical, an approach may be used where state information on the live process (process A/L in Figure 1) is periodically checkpointed by the logging means of the recovery unit from the volatile memory of the processor running the process to stable store (disc unit 10). Upon failure of the live process A/L, the recovery means of the recovery unit can bring up a replacement process A/R in a state corresponding to the last-checkpointed state of the failed live process. Of course, unless check-pointing is effected at every state change, the state of the replacement process A/R will generally be behind the actual state achieved by the live process prior to failure. This can be alleviated by having the logging means of the recovery unit securely store appropriate information on all non-deterministic events experienced by the live process between its checkpoints and then arranging for the recovery means to replay these events to the replacement process to bring it more up-to-date.

Where speed of recovery is critical, it is generally preferred to run at least one replicate process (process B/R in Figure 1) that shadows the processing of the live process B/L and receives the same non-deterministic events as the latter; in this context, the live and replicate

processes are also known as the primary and secondary processes respectively. The replicate process B/R effectively acts as a store of state information on the live process B/L. The live process and its replicate may be tightly coupled so that they are always in step, or loosely coupled with the replicate generally lagging behind the live process. Upon failure of the live process B/L the recovery means causes the replicate process to take over as the replacement process B/R; where the coupling between the live process and its duplicate is only loose, if appropriate information on the non-deterministic events experienced by the live process has been stored, the replicate may be brought more up-to-date by using this information.

The present invention is concerned with software fault-tolerant systems that employ logging to a replicate process.

It will be apparent that the overhead involved in logging recovery information is considerably greater in arrangements where the replacement process is brought up to the state of the live process at failure. In fact, it is not necessary to put the replacement process in the same state as the live process at failure; instead, the need is to put the replacement process into the last externally visible state, meaning the last state in which the recovery unit produced output either to externally of the fault-tolerant system or to other recovery units in the system. Put in other words, the requirement is that there be no lost states as perceived from externally of the recovery unit.

Because it may not be possible to control events external to the system, before any system-external output is made, the logging means of the recovery unit is generally caused either to checkpoint the live-process state information and securely store non-deterministic event information, or in the case of a loosely coupled replicate process to ensure that the latter has received the same non-deterministic event information as the live process. This procedure is known as 'output commit' and can constitute a substantial processing overhead.

The same procedure can be used in relation to output made to other recovery units in the fault-tolerant system though if this is not possible (for example, because the overhead involved in providing this ability is considered too great), then the recovery means will need to "roll back" the non-failed live processes to states consistent with the one into which the replacement process can be put. Rollback is, however, a complex procedure and generally not attractive.

It is an object of the present invention to provide a simplified arrangement for ensuring that

there are no lost states when a replicate process is promoted to take over from a failed live process.

Summary of the Invention

According to the present invention, there is provided a method of operating a fault-tolerant recovery unit for receiving and processing input messages to produce output messages, the method comprising the steps of:

(a) -- providing at least two processing entities running respective replicate application processes for processing said input messages to produce application messages, one processing entity serving as a primary processing entity and each other processing entity serving as a secondary processing entity with one said secondary processing entity acting as a sender processing entity;

(b) -- receiving the input messages at the primary processing entity and causing the replicate application process run by the latter, herein the primary process, to process these input messages;

(c) -- logging to each secondary processing entity any non-deterministic choices made by the primary process during its processing,

(d) -- causing the replicate application process run by each secondary processing entity, herein a secondary process, to process in the same order as the primary process those of the input messages already received at the primary processing entity, any non-deterministic choices logged in step (c) being used by each secondary process in place of the latter making its own non-deterministic choices during processing; and

(e) -- using the application messages produced by the secondary process run by the sender processing entity as the recovery unit output messages;

the method comprising the further steps of:

(f) -- upon failure of the primary processing entity, causing a secondary processing entity to take over the role of the primary processing entity, and

(g) -- upon failure of the sender processing entity or upon the sender processing entity taking over the role of the primary processing entity in step (f), causing another secondary processing entity, where present, to become the sender processing entity, and otherwise, using the application messages produced by the primary process as the output messages, this step (g) being effected without loss of recovery-unit output messages.

Because it is the sender processing entity that is responsible for the recovery-unit output messages, there will not be externally visible lost states should either the primary or any of the secondary processing entities fail.

Generally, though not essentially, the primary and secondary processes will be arranged to execute on separate processors. The functionality providing the fault-tolerant characteristics of the method may be implemented as part of the primary and secondary processes themselves (for example, incorporated as linked libraries) or may be provided as a separate software layer providing services to the primary and secondary processes. As regards the number of secondary processing entities, multiple secondaries can be provided though for simplicity in many cases a single secondary processing entity will be adequate and reference to "each" secondary entity or process is to be understood as encompassing the singular case.

The or each secondary processing entity may receive the input messages independently of the primary processing entity (for example, the sending source may be arranged to broadcast its messages to both the primary and secondary processing entities); in this case, the or each secondary processing entity must be explicitly informed of the messages received by the primary processing entity and their order of processing.

Preferably, however, the input messages are passed to each secondary processing entity as part of the logging of information from the primary processing entity. More particularly, in one preferred embodiment (the "late logging" embodiment), step (c) further comprises logging to the secondary processing entity(ies) each input message processed by the primary process after the latter has finished its processing of that input message, each input message so logged having associated therewith any non-deterministic choices made by the primary process when processing the message. This arrangement ensures that each secondary will process only messages already processed by the primary and that the order of processing will be the same. In another preferred embodiment (the "early logging" embodiment), step (c) further comprises logging to each secondary processing entity each input message received at the primary processing entity without waiting for the processing of the input message by the primary process, any non-deterministic choices made by the primary process in processing that input message being subsequently logged to the secondary processing entity. This embodiment may involve the secondary having to stall its processing whilst it waits for the primary to provide a non-deterministic choice required in the processing of a particular input message.

Where multiple secondary processes are provided, these can be configured in different arrangements. In a first, pass-along, arrangement the primary processing entity carries out logging to one of the secondaries which in turn effects logging to another of the secondaries and so on as required, the sender processing entity being the final entity in this logging chain. In a second, one-to-many arrangement, the primary processing entity carries out logging to all the secondary processing entities directly itself. For both arrangements, resend queues of logged items are maintained by at least one entity in order to facilitate failure recovery.

At least with the embodiments where the input messages are directly or indirectly logged by the primary processing entity to each secondary processing entity, following failure of the primary processing entity it will generally be necessary to arrange for input-message sources to resend at least their latest messages since the primary processing entity at the time of its failure may not have passed on all received input messages to the or each secondary processing entity. However, the responsibility for triggering this resending will frequently belong to a fault-tolerance manager which upon detecting a failure condition in the recovery unit, requests all input-message sources to retransmit unacknowledged messages for the recovery unit concerned.

Similarly, upon failure of the sender processing entity, it will generally be necessary for the processing entity taking over this role to resend any unacknowledged output messages since the entity taking over the sender role may be further advanced in processing than the failed sender entity so that output messages could be lost if the new sender were simply to send only its newly generated messages. To enable the new sender processing entity to resend output messages, this entity is caused to normally maintain a queueing arrangement of the application messages it generates, this queueing arrangement serving as the source of output messages for resending should the sender entity fail. Solutions other than queuing and resending output messages are also possible; thus where there are multiple secondaries, the secondary designated to take over from the sender entity should the latter fail, can be arranged to lag behind the sender entity in its processing of input messages.

In fact, the queuing of application messages is the preferred solution to avoiding the possibility of output message loss and, indeed, each processing entity advantageously maintains a resend queueing arrangement holding application messages it has generated. One reason for having more than one processing entity maintain such a queueing arrangement is that if only one processing entity were involved, then should this entity fail, reconstructing

the message queues would at best be difficult and inconvenient.

Another reason to maintain a resend queueing arrangement for application messages is to enable the retransmission of messages to another recovery unit that has suffered a failure and requires recent messages to be resent.

In order to permit the resend queueing arrangement associated with a processing entity to be kept to manageable proportions, the method of the invention preferably comprises the further step of receiving input acknowledgements acknowledging the receipt of the output messages sent by the recovery unit, and removing from the resend queueing arrangements those output messages the receipt of which has been acknowledged. The method of the invention will also preferably include the further step of outputting acknowledgements of input messages received at that one of the processing entities whose processing is currently providing the output messages. These acknowledgements may be carried by the output messages being sent to the appropriate recovery unit or may be sent separately.

Preferably, in order to facilitate non-blocking operation between recovery units or between a recovery unit and a non fault tolerant client of the recovery unit, flow control of input and output messages is utilised. Embodiments of the invention may comprise the further steps of logging application messages generated by the sender processing entity in a resend queueing arrangement of fixed length, both before the application messages have been sent and after the application messages have been sent by the sender processing entity, and halting said secondary application process if the fixed length resend queueing arrangement is full with application messages.

The queueing of output messages at a sender processing entity may be advantageously combined with the queueing of input messages. Thus preferably input messages received at both primary and secondary processing entities are logged in an input queueing arrangements of fixed length, and an acknowledgement of a particular input message is output when said particular input message is removed from the fixed length input queueing arrangement for processing by the secondary processing entity. This flow control scheme ensures that when a first receiving recovery unit's input queue is full it will receive no further messages from a second sending recovery unit.

Following failure of a processing entity, a new secondary processing entity running a new secondary process, will generally be brought up and state information transferred to it from

a non-failed processing entity. Where each processing entity has an associated resend queueing arrangement, then it would be possible to transfer the contents of the queueing arrangement of the non-failed processing entity to the resend queueing arrangement of the new entity; however, this involves a substantial overhead. Preferably therefore, such a transfer is not affected. Instead, should the new secondary processing entity become the sender entity and be requested to resend messages to a particular recovery unit undergoing failover, then the non-failed processing entity that originally transferred its state to the new processing entity, is caused to send, either directly or via a secondary processing entity, to said particular further recovery unit messages in its resend queueing arrangement that are addressed to that particular further recovery unit and are associated with states of said non-failed processing entity entered prior to it transferring its state to the new processing entity.

In one embodiment a recovery unit recovering from failure of one of its processing entities sends output messages from two different sources, thus any receiving recovery unit must be capable of handling this and also of coping with the possibility of messages being received out of order. Advantageously, therefore, the input messages contain information as to their source and, at least implicitly, their sequencing, and step (b) further involves temporarily storing input messages received out of sequence from a said source whilst awaiting receipt of missing earlier-in-sequence messages, and submitting the input messages received from the source for processing by the primary process in their correct sequencing.

In an alternative embodiment a recovery unit recovering from failure of one of its processing entities sends output messages from only one of its processing entities. Preferably, following failure of a secondary processing entity, a new secondary processing entity running a new said secondary process is brought up and responsibility for sending output messages is transferred from the primary processing entity to said new secondary processing entity. The new secondary processing entity then requests from the primary processing entity only those ouput messages required by other recovery units. This involves a far lower overhead than would checkpointing all of the stored messages at the primary processing entity since only those messages which are really required by remote recovery units are copied from the primary processing entity to the secondary processing entity.

Brief Description of the Drawings

A fault-tolerant method embodying the invention will now be described, by way of non-limiting example, with reference to the accompanying diagrammatic drawings, in which:

Figure 1 is a block diagram of a prior art fault-tolerant system;

Figure 2 is a block diagram of a fault-tolerant recovery unit implementing the present invention;

Figure 3 is a diagram illustrating the main stages occurring during normal operation of the Figure 2 recovery unit;

Figure 4 is a diagram illustrating the main stages occurring during failover of the Figure 2 recovery unit;

Figure 5 is a diagram illustrating of chained logging arrangement in a recovery unit with multiple secondaries; and

Figure 6 is a diagram illustrating a fan-out logging arrangement in a recovery unit with multiple secondaries; and

Figure 7 is a diagram illustrating the configuration of a sender unit's resend queue and a primary unit's input queue.

Best Mode of Carrying Out the Invention

Figure 2 illustrates a recovery unit of a fault-tolerant system embodying the present invention. The recovery unit comprises communicating first and second processing entities which in the present case are constituted as separate primary and secondary processing units I and II each comprising a processor 20 running software, and an appropriate communications arrangement 21 (for example, a LAN) enabling the units I and II to talk to each other; the communications arrangement 21 also enables the units I and II to talk to other system elements, such as other recovery units.

For clarity of explanation, the software run by each processing unit I, II is shown as an operating system / communications layer 22 providing a basic operational environment, a fault-tolerant services layer 23 providing services for fault-tolerant operation of application processes, and the application processes 24 themselves, conceptually running on top of the layers 22 and 23.

In the present example, only one application process 24 is illustrated, this process serving to provide some specific processing functionality involving the processing of input messages to produce output messages. This processing may involve the making of non-deterministic choices.

The processes 24 run by the units I and II are replicate application processes with the process running on the primary processing unit I acting as a primary process and the process running on the secondary processing unit II acting as a secondary process. In processing input

messages, they both progress through a succession of states and produce output; because the processes are replicates, when starting from the same initial state, they will progress through the same succession of states and produce the same output on experiencing the same succession of input messages and non-deterministic choices.

In practise, the fault-tolerant services provided by the layer 23 in Figure 2 and to be described hereinafter, can be provided either by a separate software layer, as illustrated, to discrete replicate application processes (where the term 'process' is here used in the specific sense of an executing instance of a program) or as an integral part of each replicate process (for example by inclusion as linked libraries). The illustration in Figure 2 of the provision of the fault-tolerant services by a separate software layer, has simply been chosen for clarity of explanation and the person skilled in the art will recognise that the following description is generally equally applicable to either implementation. It will also be understood that the term "process", as applied to the processes 24 is intended to be read in a general sense of executing code providing particular functionality rather than in any more formal way that could be construed as excluding the intended possibility of the fault-tolerant services code being part of the same executing program instance as the application process code.

The FT services layer 23 provides a number of services to the corresponding application process 24, though a different mix of these services are used depending on the primary / secondary nature of the processing unit concerned. Because all FT services are available in each processing unit I, II it is possible for the role of the corresponding process 24 to be changed.

The FT services layer 23, provides functionality that, for clarity, is represented in Figure 2 by five main functional blocks namely an input block 25, an output block 26, a non-deterministic choice (NDC) block 27, a log block 28, and a failover and resend control block 29. The functions of these blocks 25 to 29 depends on whether the supported process 24 is serving as the primary or secondary process as will become clear from the following description of the operation of the Figure 2 recovery unit. In this description, the epithet "primary" or "secondary" applied to any one of the element 23 to 29 indicates to which of the primary and secondary units I, II the element belongs.

Failfree Operation - "Late Logging" Embodiment

The operation of a "late logging" embodiment of the Figure 2 recovery unit will now be described with reference to the flow chart of Figure 3; the applicability of the name "late

logging" for this embodiment will become apparent below.

When an input message is transmitted to the recovery unit, it is sent to the primary processing unit I. The primary input block 25 queues the input message in an input queue 30; the ordering of messages in the queue 30 will generally correspond to their order of receipt but it is also possible to give priority to particular messages (for example, messages of a particular type or coming from a particular source). When the primary process 24 is ready to process the next input message, it takes the message appearing at the head of the queue 30 (step 50, Figure 3).

The primary process 24 then executes the processing appropriate to the input message concerned (step 51). Where this processing involves making a non-deterministic choice, the primary process asks the NDC block 27 for an appropriate choice value and supplies the block 26 with the choice function to be used (or a pointer to it) and any input parameters necessary for the choice to be made. The reason for involving the NDC block 27 is that non-deterministic choices are differently derived in the primary and secondary units I and II and by having these different behaviours contained in the NDC block, the application process 24 can function identically whether part of the primary or secondary processing unit. In the primary unit I, the NDC block 27 causes the relevant choice function to be executed and returns the non-deterministic choice value returned to process 24 (step 52). The choice value is also logged in an NDC log 31 maintained by block 27.

Any application output messages produced by the primary process as a result of it processing the input message are stored in resend queues 32 maintained by the output block 26 (step 53); these application output messages are not, however, output from the recovery unit during its normal operation. The output block 26 maintains a respective resend queue 32 for each other recovery unit in the system, the application output messages being stored in the appropriate one of these queues 32.

When the primary process 24 has finished the processing of a particular input message, it informs the log block 28 which then logs this input message to the unit II together with any non-deterministic choices made by the primary process in processing the input message (such choices being held in log 31) - see step 54.

The output of the primary log block 28 is received by the secondary log block 28 (step 55) and the latter passes the received input message to the secondary input block 25 where it is

stored in queue 30. If any non-deterministic choice was passed with the input message, the secondary log block 28 passes this choice to the secondary NDC block 27 where it is stored in NDC log 31.

The input block 25 of the secondary processing unit II thus receives only those input messages that have already been processed by the primary process, the order of receipt of these messages corresponding to the order of their processing by the primary process (the O/S and comms layer 22 ensuring ordered delivery).

The secondary process 24 processes the input messages in the order they are placed in the input queue 30 of unit II (step 56). If during this processing, a non-deterministic choice is required, the secondary process 24 does exactly the same as its primary counterpart, namely it asks the secondary NDC block 27 for an appropriate choice value and supplies the block 26 with the choice function to be used (or a pointer to it) and any input parameters necessary for the choice to be made. However, the secondary NDC block 27, instead of causing the choice function to be executed, simply returns to the secondary process the non-deterministic choice provided to it from the primary process along with the input message currently being processed by secondary process 24 (step 57). In this manner, the secondary process is subject to the same sequence of non-deterministic events (input messages and internal choices) as the primary process and will therefore follow the same sequence of internal states as the primary process.

Any application output messages produced by the secondary process 24 are output to the output block 26 of unit II where like the application output messages produced by the primary process, they are logged in resend queues 32 (step 58). However, in addition, the application output messages produced by the secondary process are also output from the processing unit II as the output messages of the recovery unit (step 59). Output messages cannot always be output from the recovery unit as soon as they are generated, for example the communications network may be busy or the remote receiving unit may not be able to accept the message. The output messages are thus queued in the appropriate resend queue 32. The resend queues comprise two parts, an unsent message part and a sent message part as will be further described below in relation to flow control.

By arranging for the application process 24 run by the secondary unit II to be responsible for the generation of the recovery-unit output messages, it is assured that the world external to the recovery unit can only be aware of the consequences of states of the process 24 that

the secondary process has already entered. Should the primary processing unit I fail, the secondary processing unit II can be promoted to the primary processing unit without any risk of there being any lost states, that is, externally visible states achieved by the primary but not the secondary. Of course, the primary process at the time of failure of the primary unit I may have achieved states not attained by the secondary process, but this does not matter as the external world is only made aware of the result of processing by the secondary process (it may also be noted that some of the states attained by the primary but not the secondary at the time of failure, will be subsequently achieved by the secondary as it processes input messages logged to it by the primary prior to its failure).

The name "late logging" given to the present embodiment derives from the fact that each input message is logged from the primary unit I to the secondary unit II only after the primary process has processed the input message. A characteristic of the late-logging embodiment is that the secondary inherently can never enter states not already entered by the primary due to the very fact that the input messages are only logged to the secondary after processing by the primary. The primary, on the other hand, can proceed with processing its input messages without waiting for the secondary to reach any particular processing stage.

Failfree Operation - "Early Logging" Embodiment

In an alternative arrangement herein referred to as "early logging", whilst the key characteristic is retained of having the recovery-unit output messages generated by the secondary process, the input messages received by the primary processing unit I are logged to the secondary processing unit II without waiting for the primary process 24 to process the messages.

Of course, in the early-logging embodiment, the secondary process in processing input messages must await receipt from the primary of any required non-deterministic choices. These choices are logged to the secondary processing unit as they are produced by the primary process, this logging being effected in such a way as to enable the secondary processing unit to relate the received choices to the previously-received input messages. It will be appreciated that the secondary process 24 may need to suspend processing of an input message pending receipt of a required non-deterministic choice from the primary processing unit.

With the early-logging embodiment, it is possible for the secondary process to enter states

not yet reached by the primary process (in particular, where the processing of an input message does not require any non-deterministic choices). However, this does not matter as such states are ones which the primary will achieve in due course in processing the input messages it already has received. Thus, even if the secondary should fail when it is ahead of the primary and has generated a recovery-unit output message not yet matched by a latest application output message from the primary, no inconsistency with the external world will result as the primary will in due course pass through the same states as the secondary achieved prior to its failure.

Failfree Operation - "Independent Input" Embodiment

A further variant is also possible, herein referred to as the 'independent input' embodiment in which, again, the key characteristic is retained of recovery-unit output message generation by the secondary, but in which the input messages are now sent to both the primary and secondary processing units independently by the originating message sources. In this case, the secondary input block 25 must await confirmation from the primary log block 28 that the primary input block 25 has received a particular input message before it is entered into the input queue 30 of unit II for processing by the secondary process 24. With this restriction, the independent-input embodiment becomes like the early-logging embodiment and thus, as with the latter, in the independent-input embodiment, the secondary process 24 may need to suspend its processing of a particular input message until it has received a needed non-deterministic choice from the primary process.

Acknowledgements

Returning now to a consideration of the late-logging embodiment of the Figure 2 recovery unit, as part of its normal operation the recovery unit sends out acknowledgements ('acks-out') of input messages it has received, and receives back from other recovery units, acknowledgements ('acks-in') of the receipt of recovery-unit output messages sent by the secondary unit II.

The acks-out will generally be 'piggy-backed' onto output messages being sent by the secondary output block 26 to the recovery unit that sent the input message being acknowledged. However, to cover the possibility of a prolonged absence of an output message to that recovery unit, it is preferably also to implement an alternative transmission mechanism, such as a time-out mechanism by which an ack-out will be sent by itself after, for example, a predetermined time, if no output message to the required recovery unit is generated in that time.

As regards acks-in, these may likewise be received 'piggy-backed' on an input message or as separately-sent acknowledgements. In either case, after receipt at the primary processing unit I, acks-in are passed to the secondary processing unit II. At both units, the acks-in are used to effect a garbage-collection operation on the resend queues 32 held by the corresponding output block 26, it no longer being necessary to keep a copy of an output message acknowledged as having been received (such an acknowledgement will only have been sent after the message concerned has been received at both the primary and secondary processing units of the recovery unit concerned).

The sending and receipt of acknowledgements is substantially the same for the early-logging and independent-input embodiments though with the latter, an ack-out is not sent by the secondary processing unit II in respect of a particular input message until the primary processing unit I has informed the secondary processing unit II that it has also received the input message.

Flow control

Acknowledgements are used in conjunction with a restriction on the length of the resend queues 32 to achieve control of the flow of messages between recovery units. This is necessary for example if a first recovery unit is sending messages to a second recovery unit at a speed which the second recovery unit is unable to process them.

Flow control is achieved by requiring that :

1) the total length (including unsent messages) of the resend queue 32 of a secondary unit II is the same as the length of the input queue 30 of the corresponding primary unit I of the recovery unit receiving these messages, and that

2) ack-outs are sent only when a message is removed from the input queue 30 of a secondary unit I and is about to be processed by the application 24.

With reference to Figure 7, the resend queue 32 of a secondary unit I has two parts. An unsent message part 70, holding messages that are waiting to be sent, is separated from a sent message part 71, holding messages which have already been sent, by a marker 72. Messages output from the application 24 enter the back of the resend queue at 73 and are sent once they reach a position 74 adjacent the marker 72. Once a message is sent the marker 72 is moved to the other side of the message so that the message is then in the sent message part 71 of the resend queue 32. If the resend queue is full the application 24 is halted so that no further messages are sent to the queue. The replicated application 24 running on the primary unit I is of course also halted. Once acknowledgements have been received and messages in the sent message part 71 of the resend queues 32 have been deleted

the applications 24 may be restarted.

The length of the resend queues 32 of both the primary and the secondary units are fixed to be the same length as the input queues 30 of both the primary and the secondary units of the remote recovery unit to which the resend queue sends messages, as shown in Figure 7. The length set for these queues is negotiated between the two recovery units when they are initially configured. Acknowledgements are then sent, as described above, from the recovery unit receiving messages to the primary unit I of the recovery unit sending messages. However, an acknowledgement is not sent when a message joins the back 75 of an input queue 30 but is only sent when it is taken from the front 76 of the input queue 30. When the sending recovery unit receives the acknowledgement, the appropriate message from the sent message part 71 of the secondary unit's resend queue 30 is deleted. This flow control process thus ensures that when a receiving recovery unit's input queue is full it will receive no further messages from a sending recovery unit.

It should be noted that the flow control process is very efficient in that it does not require any further control messages but utilises the acknowledgements which are in any case required to eliminate messages from the resend queues. Furthermore, because acknowledgements are logged from the primary unit I to the secondary unit II (to eliminate messages from both resend queues) the flow control indictions utilised are also automatically replicated at both primary and secondary units. It will be appreciated that the resend queue 32 of a primary unit I although configured in two parts as described above will normally only contain messages in the unsent message part 70.

Failure Behaviour

Having described the operation of the recovery unit in the absence of failures, consideration will now be given to the response of the recovery unit both to a failure of one of its own primary or secondary processing units and to a failure of a processing unit of another recovery unit.

If the secondary processing unit II of the Figure 2 recovery unit should fail, for whatever reason, then the failover and resend control block 29 of unit I is triggered to take appropriate action. The detection of secondary unit failure may be effected in any known manner, for example by a system unit that monitors a 'heartbeat' from each primary and secondary process; how failure detection is achieved is not material to the present invention and so will not be described further. It will be appreciated that failure of a processing unit I, II may

result from a failure internal to the application process 24, from a failure of the supporting software layers 22 and 23, or from a failure of the processor 20 of the unit; in all cases, the processing unit 24 ceases to provide the functionality of process 24 to the recovery unit.

The failover control block 29 of unit I responds to failure of the secondary unit II by bringing about the sequence of actions shown on the right-hand side of Figure 4. In particular, the application output messages generated by the primary process are now used as the output messages of the recovery unit (block 40, Figure 4) by arranging for the output block 26 of unit I to output the application messages it receives from the primary process (this output is shown dotted in Figure 2 as are all failure-related communications in this Figure). When the primary unit I is made a sender it does not know exactly what output messages the secondary-process unit II has sent prior to its failure. Two alternative arrangements are possible, firstly the primary output block 26 may resend all unacknowledged output messages in its resend queues 32. This may result in a message being sent twice (once from the secondary unit II and again from the primary unit I); however, by numbering the output messages sent to any particular recovery unit in sequential order (one sequence per destination recovery unit), each receiving recovery unit can identify and discard duplicate messages. In fact, it is only necessary to explicitly number the first output message sent from a given processing unit to a particular recovery unit since the O/S & comms layer 22 provides a guarantee of ordered, non-repeated, delivery of messages thereby enabling the sequence number of subsequent messages from the same recovery unit to be implied. Alternatively, rather than resending all the unacknowledged output messages, the primary unit I taking responsibility may query the primary units of the remote recovery units to which messages have been sent and resend only those messages which have not been received. The number of such messages will be fewer than the number of unacknowledged messages in its resend queues because messages are acknowledged by remote recovery units only once they are passed to these recovery units secondary units.

It will be appreciated that in order to uniquely identify an output message (and therefore, of course, an input message since the output messages of one recovery unit generally form the input messages of another), it is necessary to know both the sequence number of the message and the identity of the sequence concerned as, for example, identified by the source/destination combination - this latter information will, of course, generally be available as part of the message concerned. In the present specification, the reference to a sequence number of a message should be understood as referring to that sequence number in the context of the sequence concerned.

Upon failure of the secondary unit II, the primary unit I, as well as becoming responsible for the sending of recovery-unit output messages, also becomes responsible for sending acks-out.

A new secondary process is next brought up on an operative processing unit (block 41); persons skilled in the art will be aware of the details of how this may achieved and, accordingly, this step will not be further described herein. The state of the primary process 24 is then transferred to the new secondary process to synchronise the two. Exactly how this state transfer is effected is the responsibility of the primary application process 24 since this process alone will know about what state information is required; the alternative approach of making a memory image copy is not preferred as this results in propagation of uncollected garbage and similar non-useful memory contents).

Finally, the responsibility for sending recovery-unit output messages is passed from the primary processing unit I to the new secondary processing unit (block 42) and the primary unit I commences logging to the new secondary unit.

Considering next what happens upon the failure of the primary processing unit I, this failure is again detected by any suitable mechanism and this time the failover and resend control block 29 of the secondary processing unit II is triggered into action. As illustrated on the left-hand side of Figure 4, upon primary failure, the failover control block 29 causes the secondary unit II to take over the role of the failed primary unit I, the process 24 of unit II now utilising those services offered by the FT layer 23 appropriate to this primary role (block 44) including causing non-deterministic choices to be made for process 24 as required. Meanwhile, the other recovery units will have been notified to send messages to the unit II rather than the unit I. The output block 26 of the newly-promoted primary unit II temporarily remains responsible for sending output messages and acks-out but does not need to resend any output messages.

Because the failed primary processing unit I may have received input messages not logged to the processing unit II, the other recovery units are all prompted to resend any unacknowledged messages they have in their resend queues for the recovery unit that experienced the primary failure (block 45). The request for messages to be resent is generated by the newly-promoted primary processing unit II itself. Because of the sequential message numbering scheme already mentioned above, should a message already received by unit II be resent (for example, because the corresponding ack-out has not yet been

transmitted by unit II), the input block 25 of unit II can detect and discard such duplicates.

Next, a new secondary processing unit is brought up and the state of the process 24 of the newly-promoted primary unit II is transferred to the new secondary (block 46). Finally, the responsibility for the sending of output messages and acks-out is transferred to the new secondary processing unit (block 47) and the primary unit II commences logging to the new secondary unit.

When a newly created secondary process is brought up, unless the resend queues 32 from the primary output block 26 are transferred (checkpointed) to the secondary output block 26, its resend queues will be empty. Three alternative techniques can be utilised to bring these resend queues up while still sending output messages from the recovery unit.

A first technique comprises sending output messages from both the primary and secondary output blocks until the primary output block no longer contains unacknowledged output messages which were present at the time of hand back of responsibility to the secondary unit. The control block 29 associated with the primary process can detect this condition by having the corresponding output block mark any messages it has in its resend queues at the time of hand back of responsibility; if a resend request is received, it is then a simple matter for the control block 29 to check if any such marked messages still exist. If there are any such messages, then the primary output block 26 resends these messages and the secondary output block 26 resends the messages in its own resend queues. This technique requires that the FT service provided the layer 23 for the support of failover of a different recovery unit has the ability to receive messages from two different resources within the same recovery unit.

A second alternative technique, similar to the first technique, comprises delaying the transfer of responsibility from the primary unit to the secondary unit until the resend queues 32 of the secondary unit are established. The primary unit continues to send output messages, however, no output messages are sent by the secondary unit until its resend queues contain all the messages sent by the recovery unit which remain unacknowledged. At this time the primary unit stops sending output messages and the secondary unit starts sending output messages. There is thus no time at which output messages are being sent by both units. If the primary unit fails before the secondary unit begins to send messages, the recovery unit will fail completely. When employing this technique acknowledgements sent out by the primary unit must be delayed until the secondary unit has handled the message to which the

acknowledgement relates so as to prevent the secondary unit from being flooded by more messages than it can process from the primary unit. This is achieved by requiring the secondary unit, during the period it is building up its resend queue and before it assumes responsibility for sending out messages, to send acknowledgements to the primary unit. Once the primary unit receives such an acknowledgement from the secondary unit it sends out an acknowledgement to the remote recovery unit. When the secondary unit assumes responsibility it sends out acknowledgements in the normal manner.

A third technique comprises handing over responsibility to the secondary unit immediately, even though its resend queues may not contain all unacknowledged messages. The secondary unit then queries the primary units of remote recovery units as to which, if any, messages they require. Required messages are requested from the primary unit and relayed to the appropriate remote recovery unit. This technique, although similar to the checkpointing of entire resend queues known in the prior art, involves a far lower overhead since only those messages which are really required by remote recovery units are copied from the primary unit to the secondary unit.

The FT services layer 23 as well as providing FT services for supporting failover of the recovery unit itself following failure of the primary or secondary unit, also provides FT services for supporting failover of other recovery units. The most significant of these services is the resending of unacknowledged output messages sent to a particular recovery unit when requested to do so following a process failure in the latter. The resend queues 32 which have already been described are, of course, an integral part of this service. In normal operation, the output messages will be resent only from the secondary output block 26. On the other hand, if there is as yet no operative secondary processing unit because the recovery unit receiving the resend request is itself recovering from a processing-unit failure and has not yet synchronised its newly created secondary with the primary process, then the primary output block 26 is responsible for the resending of the output messages.

A further capability of the FT layer 23 is the placing in correct order output messages received from the same recovery unit. Whilst the comms layer 22 ensures the ordered delivery of messages from the output block it serves, during failover of a recovery unit, output messages will be sent from two sources, as noted above. As a result, the possibility exists that the output messages sent to another recovery unit may arrive out of order; in particular, the first one or more messages sent from a new secondary processing unit may arrive prior to older messages sent from the primary processing unit. However, because of

the afore-mentioned sequential numbering of messages (explicit or implied), it is possible for the primary input block 25 of a receiving recovery unit to correctly order its input messages before placing them in queue 30. To this end the input block may be provided with an early message queue 33 which it uses to store out of sequence messages pending receipt of the missing messages. Clearly, if either of the alternative techniques described above, which do not result in the sending of messages from two sources are utilised, an early message queue 33 is not required.

With regard to the operation of the early-logging and independent-input embodiments in failure conditions, their general operation is similar to that of the late-logging embodiment described above. Persons skilled in the art will readily be able identify and implement such variations as may be appropriate.

Multiple Secondaries

Although in the described embodiments of a recovery unit, only two replicate application processes are run (one by the primary processing entity and the other by the secondary processing entity), it is possible to run more replicate processes to increase the fault tolerance of the recovery unit. Thus, where there are n replicate application processes, in addition to the application process run by the primary processing entity, there will be (n-1) replicate application processes run by respective secondary processing entities with one of these secondary processing entities serving as a sender entity responsible for the output of recovery-unit output messages and acks-out. The sender entity operates in a manner to the secondary processing unit II of Figure 2; the non-sender secondary entities also operate like unit II with the exception that their output blocks do not send recovery-unit output messages or acks-out.

Two main arrangements are possible in the case of multiple secondary processing entities. Firstly, in a "chained" or "pass-along" arrangement, the primary entity effects its logging to a first one of the secondary entities and the latter is then responsible for logging operations to the next secondary entity, and so on as required for the number of secondary entities present; in this arrangement, the final secondary entity in the logging chain constitutes the sender entity. This chained arrangement increases the fault tolerance of the recovery unit considerably since with n entities present, the recovery unit may remain operational even if up to n-1 entities fail.

In the second arrangement, the secondary entities are arranged in a "fan-out" or "one-to-

many" configuration relative to the primary entity with the latter sending its logging messages to all secondary entities effectively in parallel; in this case, any one of the secondary entities can be chosen to serve as the sender entity. Advantages of the fan-out arrangement include that the recovery from failure is very rapid and that there is not a period of vulnerability to further failure while a new secondary entity is being configured.

Figure 5 illustrates a recovery unit 60 with a primary processing entity 61 and a chained arrangement of two secondaries 62, 63. The primary entity 61 logs input messages, non-deterministic choices and acks-in, in log messages to the secondary entity 62 which, in turn effects logging to the secondary entity 63, the latter being responsible for the generation and sending of recovery-unit output messages. As regards when logging is effected from the secondary entity 62 to the secondary entity 63, it is possible to adopt a late logging policy similar to that described above for transmission between primary and secondary entities; alternatively, an early logging policy can be applied to the logging between the entities 62 and 63, the entity 62 logging to entity 63 the input messages, non-deterministic choices and acks-in immediately entity 62 receives these items from primary entity 61. The early logging scheme obviously has a smaller latency then the late logging scheme and this difference in latency grows with the number of secondary entities present.

If the primary entity 61 fails, then secondary entity 62 takes over as the primary entity in much the same manner as already described above with reference to Figures 2 to 4; however, the secondary entity 63 remains responsible for sending recovery-unit output messages. If the secondary sender entity 63 fails, then secondary entity 62 takes over the role of sender, again in a manner similar to that described above for where the primary takes over from a failed secondary of the Figure 2 recovery unit (though, of course, the entity 62 remains in its secondary role).

If the secondary entity 62 fails (or, more generally, any interior secondary member of a logging chain), then the logging chain must be patched up with the failed entity being by-passed - in the Figure 5 example, this requires the primary entity to redirect its logging messages to the secondary sender entity 63. However, since the possibility exists that the failed interior entity 62 has not passed on to entity 63 all logs received by entity 62 prior to its failure, it is generally necessary for all processing entities other than the last two in the logging chain to maintain a log resend queue of log messages it has sent, the messages in this resend queue being sent to the next-but-one downstream entity in the logging chain should the adjacent downstream entity fail. It is obviously unnecessary for the ultimate entity

in the logging chain to maintain a log resend queue as it does not carry out any logging; as regards the penultimate entity, this does not need to maintain a log resend queue since if the entity to which it logs should fail (that is, the final, sender entity) then the penultimate takes over as the sender entity and it not required to effect logging.

The log resend queues must, of course, be managed to remove those log messages it is no longer necessary to resend (because they have been received by at least the next two downstream entities). One possible way of achieving the desired management is by the use of explicit acknowledgements sent to all entities maintaining a log resend queue by the last secondary entity of the logging chain as log messages are received by this latter entity; each entity receiving such a log acknowledgement then deletes the corresponding log message from its log resend queue. A refinement of this approach is to have the last secondary entity of the logging chain only send acknowledgements to the primary entity which then forwards these acknowledgements along the logging chain, preferably piggy-backed to later log messages. It may be noted that with only two secondary entities (as in Figure 5), the explicit acknowledgement approach reduces to the secondary sender entity 63 sending acknowledgements to the primary entity 61.

An alternative approach to managing the log resend queues is to use implicit acknowledgments. In this case, each log message in a log resend queue has associated with it the sequence number of the output message that is first generated by the primary process following the latter taking for processing the input message which is contained in the log message. Acks-in acknowledging receipt of output messages are delivered to the primary entity by the receivers of these output messages in the usual way. When a processing entity receives such an ack-in, any log message in its log resend queue (where maintained) that has an associated output-message sequence number equal to or less than that to which the ack-in relates can be garbage collected - this is so because the corresponding output message will only have been output from the recovery unit after receipt of the corresponding log message by the sender entity.

The implicit acknowledgement scheme is only efficient if output messages are frequently generated; accordingly, the implicit acknowledgement scheme is preferably operated with a fall back to the sending of explicit acknowledgements if, for example, the size of the log resend queue exceeds a predetermined limit.

Figure 6 illustrates a recovery unit 65 with a primary processing entity 66 and a fan-out

arrangement of three secondaries 67, 68 and 69, the secondary entity 69 serving as the sender entity. The primary entity 61 logs input messages, non-deterministic choices and acks-in, in log messages to all secondary entities 67, 68 and 69, this logging being effected according to the early logging or late logging scheme already described above.

If the sender entity 69 fails, then one of the other secondary entities 67, 68 is made the sender entity, the secondary entity taking over the sender role generally being predesignated as the standby sender (though this is not essential). Since the new sender entity has been sent all log messages from the primary entity, the processing sequence of this new sender is uninterrupted and so there is no need to transmit any state information, or retransmit any log messages, from the primary entity to the new sender. However, because the new sender entity may have reached a state in advance of the failed sender entity at the time of failure of the latter, the new sender entity must send any unacknowledged application output messages in its output-message resend queue. In fact, it possible to avoid having to resend output messages by arranging for the secondary entity designated as the standby sender, to lag behind the current sender entity in its processing so that when the designated standby sender takes over the sender role upon failure of the original sender, this new sender entity will continue its processing from a state behind that achieved by the failed sender entity at its point of failure. The standby sender can be caused to lag behind the original sender entity prior to failure of the latter by arranging for the standby sender to delay processing an input message until after it has received an indicator from the sender entity that the latter has finished its processing of that input message (this indicator could be sent following output of any output message generated by the processing of the input message concerned).

If the primary entity 66 fails, then the most advanced of the secondary entities 67 to 69, is arranged to take over the primary role. Determination of which secondary is most advanced is effected by an exchange of messages between the secondary entities. By having the most advanced secondary become the primary, it is assured that none of the remaining secondaries has already entered a state not achieved by the new primary (such a situation could lead to divergence between the new primary and one or more of the secondaries). However, it is possible that some of the remaining secondaries may not have received all log messages received by the new primary when it was itself a secondary; accordingly, the new primary must resend log messages to the remaining secondaries. To this end, each of the original secondaries is required to keep a log resend queue of log messages it has received. These log resend queues are managed by an explicit acknowledgement scheme that involves each secondary sending an acknowledgement back to the primary upon receipt of a log message;

once the primary has received acknowledgements from all secondaries in respect of a particular log message, it sends out a garbage-collect indication in respect of that log message to all the secondaries authorising them to remove that message from their log resend queues. The garbage-collect indications can conveniently be piggybacked on later log messages sent by the primary.

Of course, if the most advanced secondary at the time of failure of the primary is the sender entity, then one of the remaining secondaries must take over the role of the sender in the manner already described; however, this new sender need not effect a resend of any output messages since this new sender will not, by definition, be in a more advanced state than the old sender that has been promoted to become the primary entity.

Rather than having the most advanced secondary take over the primary role upon failure of the original primary, it is alternatively possible to have a predesignated one of the secondaries (such as the sender) take over as the new primary. However, in this case since the new primary may lag behind one or more of the remaining secondaries, the new primary must be rolled forward to the state of the most advanced of the remaining secondaries. To this end, the new primary tells the remaining secondaries of the latest log message it has received and these secondaries then send to the primary any later log messages they have in their log resend queues (these queues are maintained in the manner already described above). The primary then uses these log messages to roll forward (this involves the new primary temporarily continuing to act as a secondary in terms of its use of non-deterministic choices in the log messages); at the same time, the new primary outputs to all secondaries both any log messages in its log resend queue and the new log messages passed to it thereby to ensure that all the secondaries have received all log messages (of course, if a secondary has already received a log message, it will discard any new copy sent to it).

Variants

Many variants are, of course, possible to the described embodiments of the invention.

Thus, although the primary and secondary processing entities are shown in Figure 2 as separate units with their own respective processors 20, it would be possible to overlap the primary and secondary processing entities by having a common processor 20 and O/S and comms layer 22 upon which the replicate primary and secondary application processes are run. In this case, a single, common, FT services layer 23 could be provided for both

replicates or else a respective FT layer could be provided for each (where the FT services are included as linked libraries with the application processes 24 themselves, then, only the latter possibility exists). Running both primary and secondary replicates on the same processor 20 does, of course, limit the type of failure protected against to those parts that are replicates, namely the actual application process itself and, where separately provided for each replicate, the FT services software.

Furthermore, several different application processes may be run above the software layers 22 and 23 on the same processor 20. In this case, the distribution between processors 20 of the primary and secondary replicates of an application may differ from application process to application process. Thus, a processor 20 with its software layers 22 and 23 may form together with a replicate application process of a first application a primary processing entity in respect of that first application, whilst at the same time forming together with a replicate process of a second application, a secondary processing entity in respect of that second application.

It is worthy of note that the FT services layer 23 can be used with non-replicated processes to integrate these processes into an overall system including the described recovery unit. These non-replicated processes are generally not critical to a system but need to behave in a manner consistent with the operation of the recovery units that have replicated application processes. To this end, each non-replicated process interacts with a FT services layer in the same manner as a replicated process but now the FT services layer is set to operate as for a primary processing unit in the case where there are no secondary units (so that the primary unit is responsible for sending output messages and ack-outs). Services such as output message resends are thereby made available to the non-replicated process. Of course, the non-replicated process need not be capable of transferring state information to a secondary as is required for process 24.

It is also worthy of note that the described recovery unit operates in a pipe-lined manner, the primary processing entity of the recovery unit being capable of starting the processing of a new input message prior to the sender processing entity outputting any output message produced by the processing of the previous input message.

CLAIMS

1. A method of operating a fault-tolerant recovery unit for receiving and processing input messages to produce output messages, the method comprising the steps of:

(a) -- providing at least two processing entities running respective replicate application processes for processing said input messages to produce application messages, one said processing entity serving as a primary processing entity and each other said processing entity serving as a secondary processing entity with one said secondary processing entity acting as a sender processing entity;

(b) -- receiving said input messages at said primary processing entity and causing the said replicate application process run by the latter, herein the primary process, to process these input messages;

(c) -- logging to each said secondary processing entity any non-deterministic choices made by the primary process during its processing,

(d) -- causing the replicate application process run by each secondary processing entity, herein a secondary process, to process in the same order as the primary process those of said input messages already received at the primary processing entity, any said non-deterministic choices logged in step (c) being used by each secondary process in place of the latter making its own non-deterministic choices during processing; and

(e) -- using the application messages produced by the secondary process run by the sender processing entity as the recovery unit output messages;

said method comprising the further steps of:

(f) -- upon failure of the primary processing entity, causing a said secondary processing entity to take over the role of the primary processing entity, and

(g) -- upon failure of the sender processing entity or upon the sender processing entity taking over the role of the primary processing entity in step (f), causing another of said secondary processing entities, where present, to become the sender processing entity, and otherwise, using the application messages produced by said primary process as said output messages, this step (g) being effected without loss of recovery-unit output messages.

2. A method according to claim 1, wherein step (c) further comprises logging to each said secondary processing entity each input message processed by said primary process after the latter has finished its processing of that input message, each input message so logged having associated therewith any said non-deterministic choices made by the primary process when

processing the message.

3. A method according to claim 1, wherein step (c) further comprises logging to said each said secondary processing entity each input message received at said primary processing entity without waiting for the input message to be processed by the primary process, any said non-deterministic choices made by the primary process in processing that input message being subsequently logged to each said secondary processing entity.

4. A method according to claim 1, wherein each said secondary processing entity receives said input messages independently of their reception by the primary processing entity.

5. A method according to any one of claims 1 to 4, wherein at least two said secondary processing entities are provided, step (c) being effected in a pass-along manner with the primary processing entity effecting said logging to one said secondary processing entity and this entity in turn effecting logging to another said secondary processing entity and so on as required, the said sender processing entity being the final entity in this logging chain.

6. A method according to claim 5, including the steps of:

-- maintaining at least one resend queue of items logged in step (c), and

-- upon failure of an intermediate said secondary processing entity in said logging chain, resending at least certain of said items from said resend queue to the secondary processing entity following the failed said secondary processing entity in the logging chain.

7. A method according to claim 6, wherein a respective said resend queue is maintained by at least each said processing entity other than the last two in said logging chain, the items in each such queue being those sent out by the corresponding processing entity.

8. A method according to claim 6 or claim 7, including causing the last said processing entity in said logging chain to output an indicator upon receipt of a said item logged to it, and using said indicator to initiate removal of said item from the or each said resend queue.

9. A method according to any one of claims 1 to 4, wherein at least two said secondary processing entities are provided, step (c) being effected in a one-to-many manner with the primary processing entity effecting said logging to all said secondary processing entities.

10. A method according to claim 9, including the further steps of:

-- maintaining for each secondary processing entity a resend queue of items logged to that entity in step (c), and

-- upon a said secondary processing entity being promoted in step (f) to become the primary processing entity, using said resend queues to ensure that all remaining processing entities have received the same logged items whereby to enable such entities to be rolled forward to the same states.

11. A method according to claim 10, wherein step (f) involves determining which of said secondary processing entities has its application process most advanced, promoting that processing entity to be the primary processing entity, and sending to the remaining secondary processing entities at least certain items from the said resend queue of the new primary processing entity.

12. A method according to claim 10, wherein step (f) involves forwarding to the new primary processing entity from said resend queues of the remaining secondary processing entities, any said items that are present in the latter queues but not in the resend queue of the new primary processing entity, and using these forwarded items to roll forward the primary processing entity.

13. A method according to any one of claims 9 to 12, including causing each secondary processing entity to output an indication upon receipt of a said item logged to it, and initiating removal of said item from said resend queues when all said secondary processing entities have produced a said indication in respect of a particular said item.

14. A method according to any one of claims 1 to 4, wherein only one said secondary processing entity is provided.

15. A method according to claim 1, comprising the additional step, following failure of a said processing entity, of bringing up a new secondary processing entity running a new said secondary process and transferring to this new secondary process state information on a said replicate application process running on a non-failed said processing entity of the recovery unit.

16. A method according to claim 15, wherein only one said secondary processing entity is normally provided, said additional step further comprising, upon the state-information

transfer being complete, of causing the new secondary processing entity to serve as said sender processing entity.

17. A method according to claim 1, wherein said input messages contain information as to their source and, at least implicitly, their sequencing, and wherein step (b) further involves temporarily storing input messages received out of sequence from a said source whilst awaiting receipt of missing earlier-in-sequence messages, and submitting the input messages received from said source for processing by said primary process in their correct sequencing.

18. A method according to claim 1, including the further steps of:

-- logging in a resend queueing arrangement the said application messages generated by that one of said replicate application process which according to step (g) is to have its application messages used as said output messages in the event of failure of the sender processing entity; and

-- resending from said resend queueing arrangement at least some of the application messages held therein upon failure of the sender processing entity.

19. A method according to claim 1, including the further steps of:

-- logging in a resend queueing arrangement the said application messages generated by the sender processing entity; and

-- resending from said resend queueing arrangement at least some of those output messages destined for a particular further said recovery unit on failover of the latter.

20. A method according to claim 1, including the further steps of:

-- logging in a respective resend queueing arrangement the said application messages generated by each said replicate application process;

-- following failure of a said processing entity:

-- bringing up a new secondary processing entity running a new said secondary process,

-- providing said new secondary process with an associated said resend queueing arrangement, and

-- transferring to said new secondary process state information, but not logged application messages, associated with a said replicate application process running on a non-failed said processing entity of the recovery unit; and

-- upon failover of a particular further said recovery unit, resending from said resend queueing arrangement associated with the secondary process run by the sender

processing entity, at least some of the messages logged therein that are addressed to said particular further said recovery unit;

this latter step involving, when said sender processing entity is formed by said new secondary processing entity, causing said non-failed processing entity to send to said particular further recovery unit application messages in its resend queueing arrangement that are addressed to said particular further recovery unit and are associated with states of said non-failed processing entity entered prior to the said transferring of state information to said new secondary processing entity.

21. A method according to any one of claims 18 to 20, including the further step of receiving input acknowledgements acknowledging the receipt of said output messages, and removing from said resend queueing arrangements those output messages the receipt of which has been acknowledged.

22. A method according to claim 1, including the further step of outputting acknowledgements of input messages received at that one of the processing entities running the said replicate application process whose application messages are currently being used as said output messages.

23. A method according to claim 1, wherein each said processing entity comprises a respective processor running the corresponding said replicate application process.

24. A method according to claim 1, wherein said processing entities share a common processor on which said replicate application processes are run.

25. A method according to claim 1, including the further steps of:

-- logging in a resend queueing arrangement of fixed length the said application messages generated by the sender processing entity both before said application messages have been sent and after said application messages have been sent by the said sender processing entity, and

-- halting said secondary application process if said fixed length resend queuing arrangement is full with application messages.

26. A method according to claim 25, including the further steps of:

-- logging in an input queueing arrangement of fixed length the said input

messages received at said primary and secondary processing entities, and

-- outputting an acknowledgement of a particular input message when said particular input message is removed from said fixed length input queueing arrangement for processing by said secondary processing entity.

27. A method according to claim 26, including the further step of, upon initial configuration of a recovery unit, negotiating with each of the further recovery units with which input or output messages will be exchanged to set appropriate fixed lengths for each of the input queueing arrangements and resend queueing arrangements.

28. A method according to claim 1, comprising the additional steps, following failure of a secondary processing entity, of

-- bringing up a new secondary processing entity running a new said secondary process, transferring to said new secondary processing entity responsibility for sending output messages, and

-- causing said new secondary processing entity to request from said primary processing entity only those output messages required by other said recovery units.

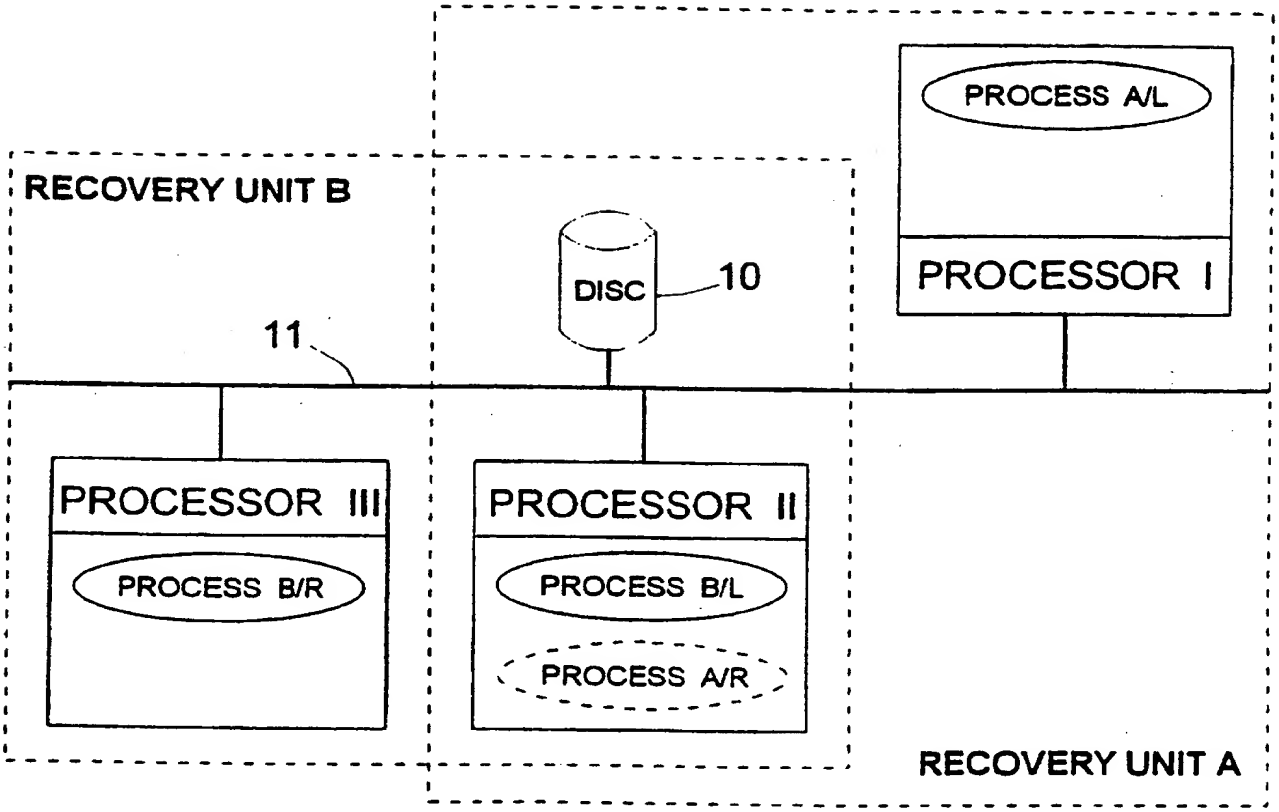

FIG. 1

(PRIOR ART)

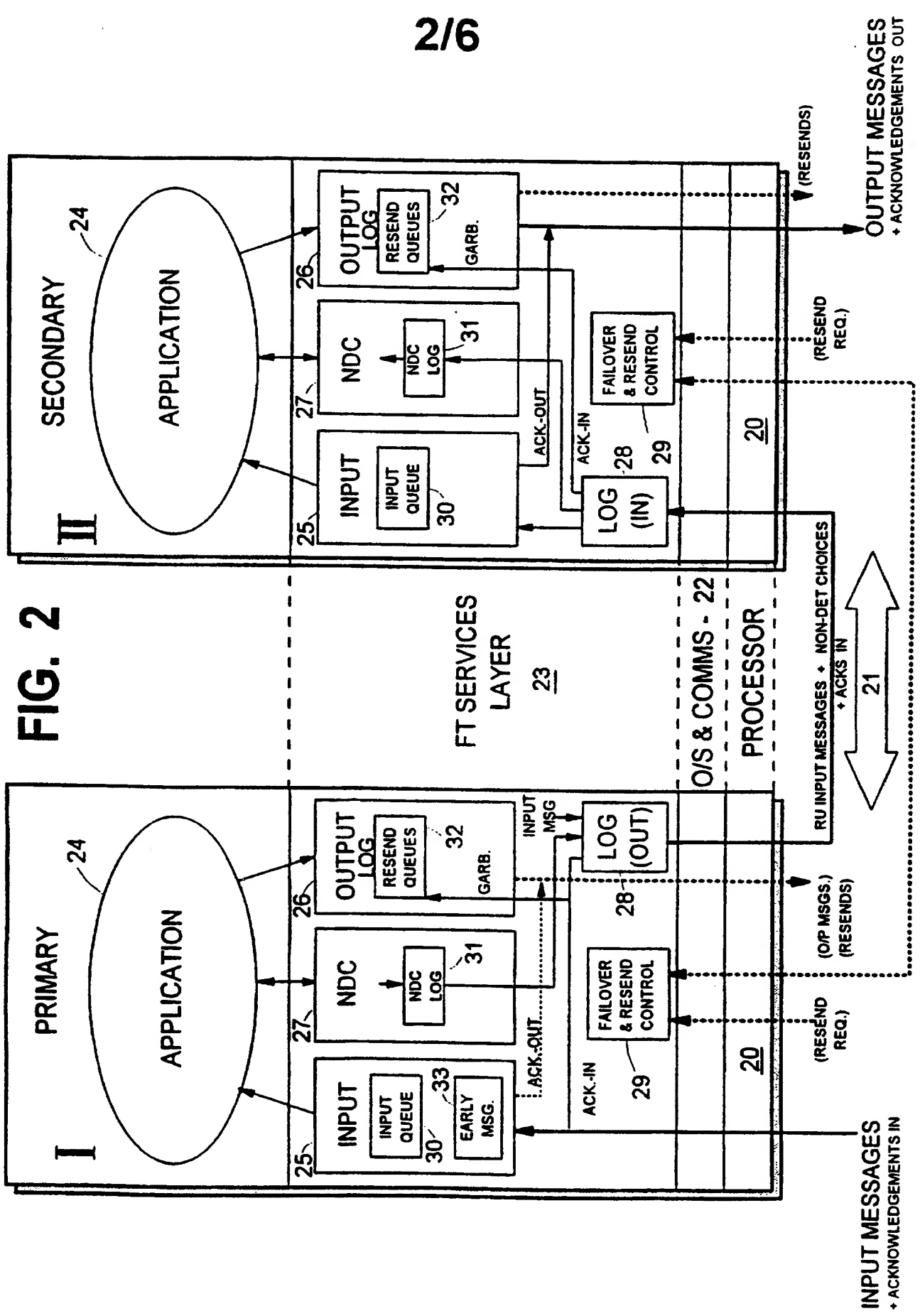
PRIMARY
I
APPLICATION
24
INPUT
INPUT QUEUE
30
EARLY MSG.
33
25
NDC
NDC LOG
31
27
OUTPUT LOG
RESEND QUEUES
32
GARB.
26
ACK.-OUT
ACK.-IN
INPUT MSG
LOG (OUT)
28
FAILOVER & RESEND CONTROL
29
FT SERVICES LAYER
23
O/S & COMMS - 22
PROCESSOR
20
21
RU INPUT MESSAGES + NON-DET CHOICES
+ ACKS IN
(O/P MSGS.)
(RESENDS)
(RESEND REQ.)
INPUT MESSAGES
+ ACKNOWLEDGEMENTS IN
SECONDARY
II
APPLICATION
24
INPUT
INPUT QUEUE
30
25
NDC
NDC LOG
31
27
OUTPUT LOG
RESEND QUEUES
32
GARB.
26
ACK.-OUT
ACK.-IN
LOG (IN)
28
FAILOVER & RESEND CONTROL
29
20
(RESENDS)
(RESEND REQ.)
OUTPUT MESSAGES
+ ACKNOWLEDGEMENTS OUT

FIG. 2

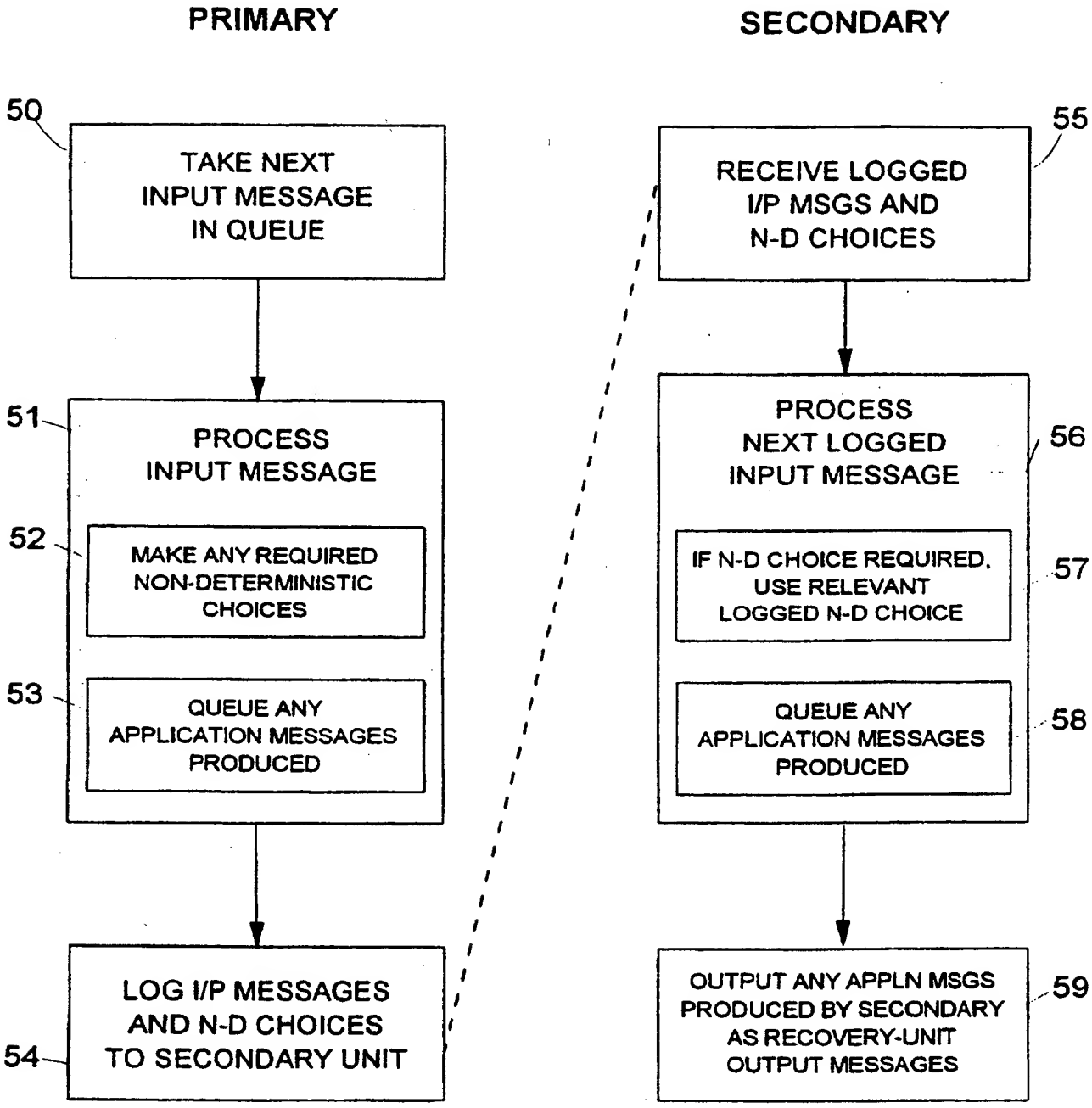
PRIMARY
SECONDARY
50
TAKE NEXT INPUT MESSAGE IN QUEUE
51
PROCESS INPUT MESSAGE
52
MAKE ANY REQUIRED NON-DETERMINISTIC CHOICES
53
QUEUE ANY APPLICATION MESSAGES PRODUCED
54
LOG I/P MESSAGES AND N-D CHOICES TO SECONDARY UNIT
55
RECEIVE LOGGED I/P MSGS AND N-D CHOICES
56
PROCESS NEXT LOGGED INPUT MESSAGE
57
IF N-D CHOICE REQUIRED, USE RELEVANT LOGGED N-D CHOICE
58
QUEUE ANY APPLICATION MESSAGES PRODUCED
59
OUTPUT ANY APPLN MSGS PRODUCED BY SECONDARY AS RECOVERY-UNIT OUTPUT MESSAGES

FIG. 3

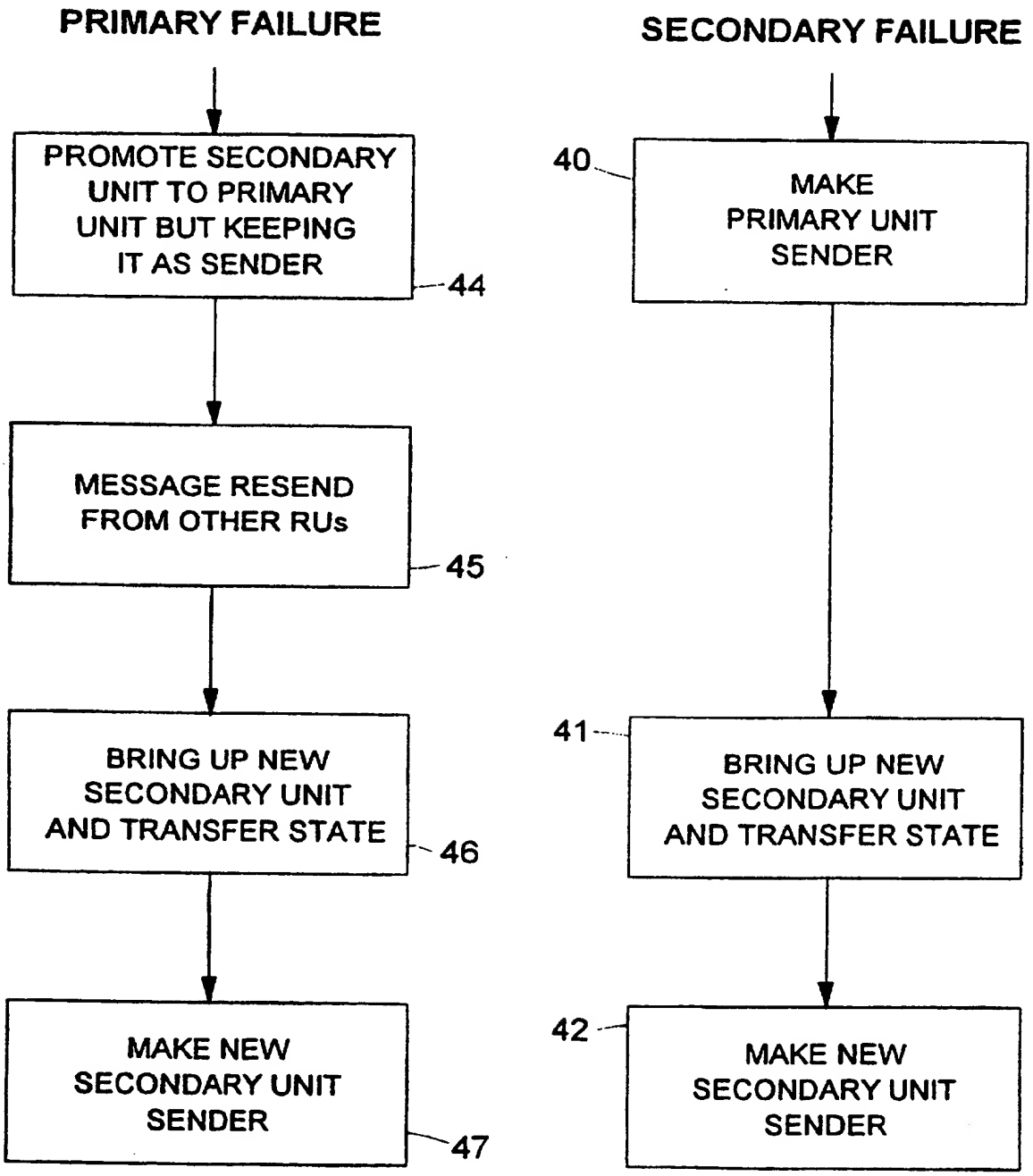
PRIMARY FAILURE
PROMOTE SECONDARY UNIT TO PRIMARY UNIT BUT KEEPING IT AS SENDER
44
MESSAGE RESEND FROM OTHER RUs
45
BRING UP NEW SECONDARY UNIT AND TRANSFER STATE
46
MAKE NEW SECONDARY UNIT SENDER
47
SECONDARY FAILURE
40
MAKE PRIMARY UNIT SENDER
41
BRING UP NEW SECONDARY UNIT AND TRANSFER STATE
42
MAKE NEW SECONDARY UNIT SENDER

FIG. 4

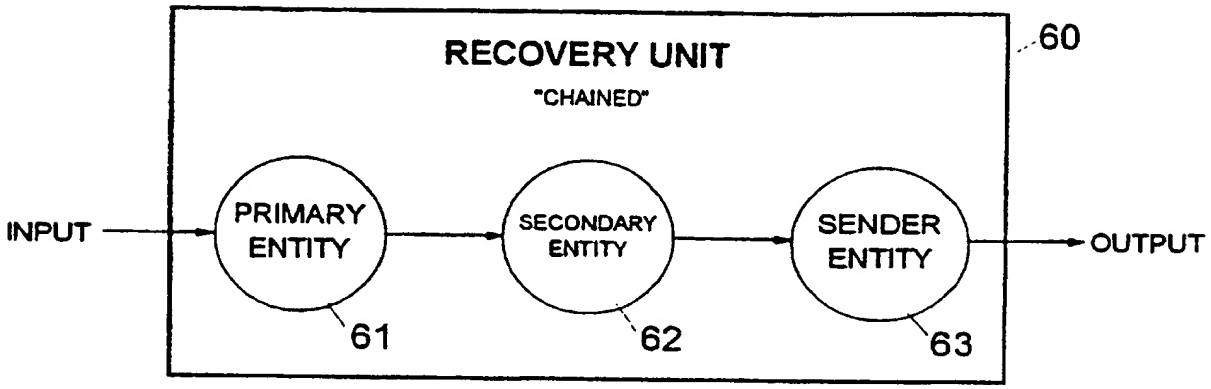

FIG. 5

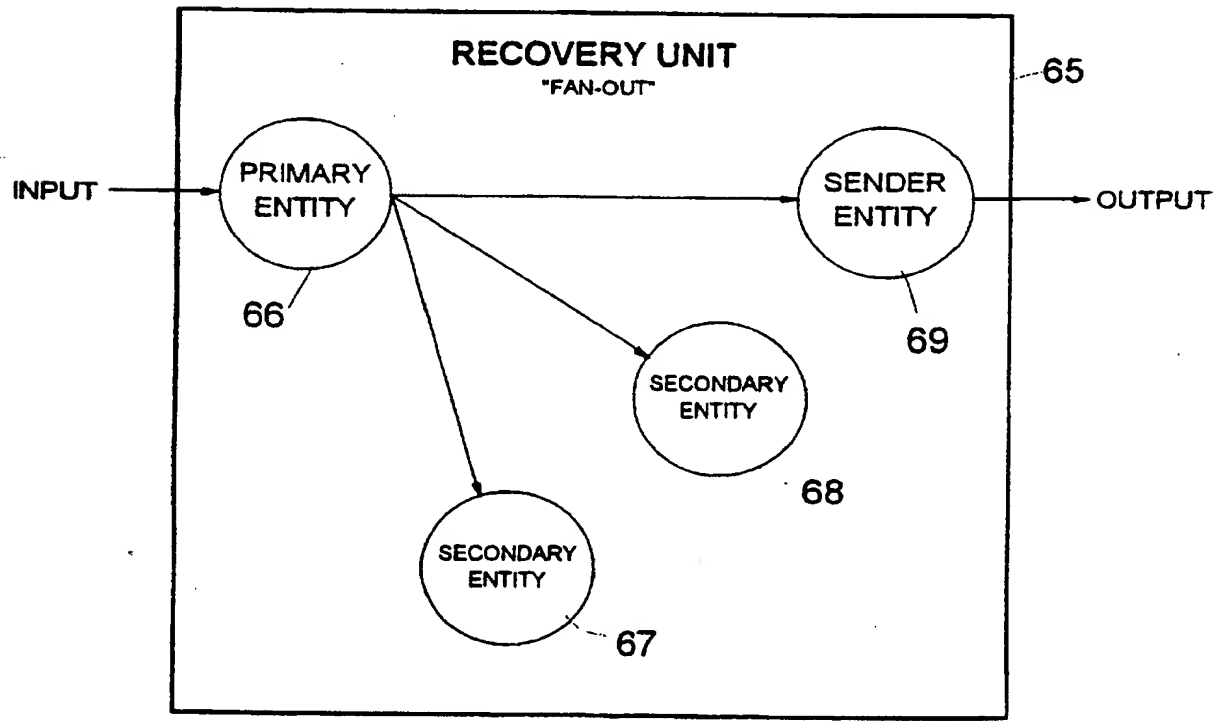

FIG. 6

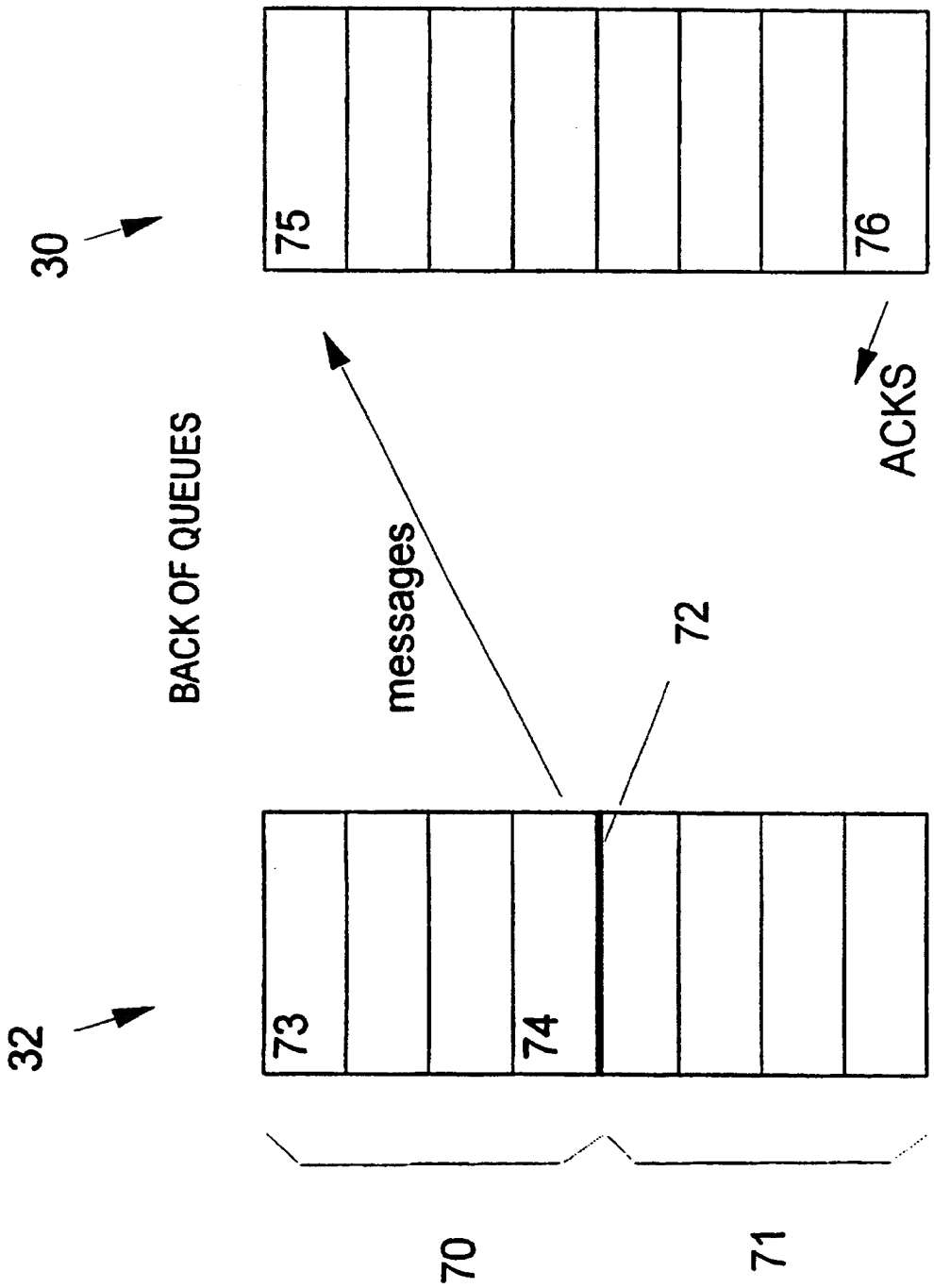
30
75
76
BACK OF QUEUES
messages
ACKS
FRONT OF QUEUES
72
32
73
74
70
71

FIG. 7

INTERNATIONAL SEARCH REPORT

Int onal Application No
PCT/GB 97/00228

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G06F11/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	INTERNATIONAL SYMPOSIUM ON FAULT TOLERANT COMPUTING. (FTCS), CHICAGO, JUNE 20 - 23, 1989, no. SYMP. 19, 20 June 1989, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, pages 184-190, XP000089476 SPEIRS N A ET AL: "USING PASSIVE REPLICATES IN DELTA-4 TO PROVIDE DEPENDABLE DISTRIBUTED COMPUTING" see page 184, right-hand column, line 9 - line 17 see page 185, left-hand column, line 20 - line 31 see page 186, left-hand column, line 4 - page 187, left-hand column, line 9 --- -/--	1-3,9, 17,21,23

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
25 April 1997	28. 05. 97
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax (+ 31-70) 340-3016	Authorized officer Masche, C

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INTERNATIONAL SEARCH REPORT

Inte nal Application No
PCT/GB 97/00228

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 665 520 A (STROM ROBERT E ET AL) 12 May 1987 see the whole document ---	1,2,4, 14,17,23
A	ACM TRANSACTIONS ON COMPUTER SYSTEMS, vol. 7, no. 1, February 1989, pages 1-24, XP000037157 BORG A ET AL: "FAULT TOLERANCE UNDER UNIX" see page 4, line 7 - line 14 see page 4, line 35 - page 5, line 18 see page 7, line 26 - line 35 see page 9, line 3 - page 12, line 3 see page 17, line 16 - line 37 ---	1,23,24, 28
A	WO 93 15461 A (UNISYS CORP) 5 August 1993 see abstract see page 9, line 9 - page 12, line 14 see page 25, line 27 - page 26, line 11 see figure 3 -----	1

1

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte nal Application No
PCT/GB 97/00228

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4665520 A	12-05-87	CA 1223369 A	23-06-87
WO 9315461 A	05-08-93	US 5363503 A	08-11-94
		EP 0623230 A	09-11-94
		JP 7503334 T	06-04-95